Patterns of bedform migration and mean tidal currents in Hampton Harbor Inlet, New Hampshire USA

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DEDICATION

This thesis is dedicated to my parents, my brother, and my grandparents for encouraging me to return to graduate school, and for providing love and support through this entire process.
ACKNOWLEDGEMENTS

This work was sponsored by the National Oceanic and Atmospheric Administration and the Office of Naval Research. This study would not have been possible without the support and assistance of the entire community at the University of New Hampshire Center for Coastal and Ocean Mapping Joint-Hydrographic Center. I would especially like to thank my thesis advisor, Dr. Tom Lippmann, for all the guidance he provided me throughout my graduate education. I am also grateful to my thesis committee, Dr. Larry Ward, Dr. Yuri Rzhanov, and Dr. Diane Fosters for all of their insight and help with my research. I would also like to thank the following faculty for providing me much needed research assistance and support when I most needed it: Dr. Brian Calder, Dr. Semme Dijkstra, Dr. Jonathan Beaudoin, Roland Arsenault, Glen Rice, Val Schmidt, and Dr. Edith Gallagher. I am also very grateful to all those that provided field work support and assistance: Dr. Jim Irish, Jon Hunt, and Zack Laforet. I am most appreciative to Captain Ben Smith and Captain Emily Terry, for without them this study would not have been possible. Thank you to Larry Mayer and Andy Armstrong for allowing me to join the CCOM community and funding me for three years. Thanks also to the IT staff for constantly updating and fixing all the computers used in this study. Thank you Kurt Murphy for ortho-rectifying the historical images used in this study. Many thanks to my past and present fellow graduate students who provided constant advice, encouragement, and friendship: Kevin Jareem, Monica Wolfson, Tami Beduhn, Chris Englert, Ashton Flinders, Garrett Mitchell, Meagan Wengrove, Emily Carlson, and Sylvia Rodriguez-Abudo. I also want to thank my parents for encouraging me to pursue
my masters, and my brother, Brian, for mocking me and my research in true older brother fashion, but then saving me at the last minute when I got stuck coding. And finally a very special acknowledgment and thank you to Christy Fandel and Evan Gray, the best best friend and boyfriend a girl could ask for.
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ABSTRACT

PATTERNS OF BEDFORM MIGRATION AND MEAN TIDAL CURRENTS IN HAMPTON HARBOR INLET, NEW HAMPSHIRE, USA

by

Lindsay A. McKenna

University of New Hampshire, May, 2013

High-resolution seafloor topography and coincident mean currents were obtained in Hampton Harbor Inlet over a fortnightly tidal cycle. Nine multibeam echosounder surveys were conducted in the inlet navigation channel, and mean currents were measured throughout the inlet using an acoustic current profiler mounted on a movable personal watercraft. Maximum mean currents of 1.5 m/s were observed and coherent bedforms, ranging in size from sand dunes to mega-ripples, were present throughout the inlet navigation channel. Spatial variation in bottom roughness showed that mega-ripples evolved spatially and temporally over the study. A series of 8 sand dunes migrated steadily onshore, up to 8 m, during neap tides and steadily offshore, up to 15 m, during spring tides. The net movement of sand dunes over the study was offshore, indicating higher flows during spring tides that dominated net sediment transport. Higher shear stress estimates during spring tide validate observations of bedform migration.
CHAPTER 1

INTRODUCTION

The Hampton Harbor Inlet serves as the only connection between the Atlantic Ocean and Hampton-Seabrook estuary, the second largest estuary system in the state of New Hampshire, USA. Located between the townships of Hampton Beach and Seabrook Beach, the Hampton Harbor Inlet, is an important economic, recreational, and ecological asset. The Hampton-Seabrook Estuary back-barrier system contains over 4,000 acres of salt marsh, and supports many important coastal ecosystems including the most productive softshell clam bed in New Hampshire (Eberhardt and Burdick, 2009). Additionally, annual revenue of the commercial and recreational boating industry based out of Hampton Harbor is estimated at over $5 million (Cecil Group, 2001). The US Army Corps of Engineers (USACE) is responsible for maintaining a navigation channel directly down the center of the inlet. Owing to a large flux of sediment in the inlet, the navigation channel is dredged regularly at roughly 5-year intervals to maintain safe navigation depths of greater than 2.4 m MLLW, mean lower low water, (Pease Development Authority, 2012; henceforth PDA, 2012).

A large mean tidal range of 2 m drives saltwater flow into and out of the estuary, creating strong currents in the inlet channel that oscillate with the tide. Maximum current magnitudes in the inlet are quite high, exceeding 1.5 m/s during peak flows (Eberhardt and Burdick, 2009). Jetties bounding the entrance of the Hampton Harbor Inlet cause
Tidal currents to increase in magnitude through the inlet channel during flooding tides, and drainage of the large estuary leads to strong current magnitudes during ebb tides.

Inlet sediments consist of medium-to-coarse grained quartz sand, and observations presented herein show that the inlet navigation channel is characterized by bedforms ranging in scale from sand dunes (amplitudes of 1-2 m and wavelengths of 20 to 40 m), to mega-ripples (amplitudes of 0.1 to 0.3 m and wavelengths of 1-10 m). The bedforms migrate with the tides, changing in size, shape, and location. The large amplitude sand dunes in conjunction with the shallow depths of the inlet cause dynamic navigational hazards within the navigation channel.

This study analyzes observations of bedform migration and current flows over a fortnightly tidal cycle in the Hampton Harbor Inlet in the fall of 2011. Chapter 2 focuses on observations of seafloor topography and bedform migration, and describes the methods used to collect bathymetry measurements and analyze bedform migration in the inlet navigation channel. Chapter 3 focuses on observations of mean currents over the entire inlet. Current measurements were obtained using a small maneuverable vessel that can safely transit very shallow waters. Shear stresses were estimated by calculating friction velocities and Shields parameters, derived from mean current profiles. Estimates of shear stress are compared to bedform migration observations.

The following two chapters are presented as individual scientific papers. Each chapter has its own abstract, introduction, methods, results, discussion, and conclusion sections. The final chapter provides a short synopsis of the entire study.
CHAPTER 2

MORPHOLOGICAL EVOLUTION OF A TIDALLY MODULATED INLET

2.1 Abstract

The morphodynamics of a tidally modulated inlet were characterized using a combination of bathymetric surveys, hydrodynamic measurements, and sediment sampling. The Hampton Harbor Inlet, leading to Hampton Harbor, New Hampshire, USA, is approximately 1 km in length and 300 m wide, with bottom sediments consisting of medium-to-coarse grained quartz sand (Tuttle, 1960). A 100 m wide navigation channel is maintained through the center of the inlet. Bedforms within the inlet navigation channel were observed with repeated high-resolution multibeam echosounder (MBES) surveys in the fall of 2011 between 21 September and 17 October. A total of nine bathymetric surveys of the inlet navigation channel were conducted, with three of the surveys occurring over one day. Bedforms, classified according to Ashley, 1990 and Fredsøe and Deigaard, 1992, ranged in size from mega-ripples - with 0.1-0.3 m amplitudes and 1-10 m wavelengths - to sand dunes with 1-2 m amplitudes and 20-40 m wavelengths. Observations suggest that net integrated volume migrations of sand dunes were up to 8 m onshore during the neap tide, and up to 15 m offshore during the spring tide. Mega-ripples were observed throughout the inlet on both flat seafloor and superimposed on top of the larger sand dunes. The mega-ripples evolved spatially and
temporally throughout the inlet, and root-mean-square amplitudes fluctuated with the fortnightly tidal cycle. While the net migration of sediment over the study period was offshore, higher temporal resolution surveys show that bedforms of varying scale change in space and time over bi-weekly periods, with sediment observed to migrate in the onshore and offshore directions.

2.2 Introduction

Shallow marine environments are often characterized by an erodible seabed of unconsolidated sedimentary material consisting of a variety of grain sizes and mineralogies. Beaches, inlets, and estuaries are generally associated with wave-driven, wind-driven, and tide-driven currents, as well as surface gravity waves, all of which can greatly influence the nature of the coastline morphology and character of the seafloor. Common characteristics of seafloor morphologies include sand bars and shoals at large scales, with wavelengths on the order of 10's to 100's of meters, and a variety of bedforms at smaller scales, with wavelengths on the order of 1 to 10's of meters (e.g., Whitmeyer and Fitzgerald, 2008).

Bedforms are important for several reasons which include their: association with increased turbulent stresses (e.g., Passchier and Kleinhans, 2005); role in the transport of sediment (e.g., Van Den Berg, 1987); and recorded geological history (e.g., Moslow and Tye, 1985; Myrow and Southard, 1991). The regularity of bedform wavelength, amplitude, and orientation suggests a strong feedback mechanism between flow and sediment transport (e.g., Gallagher, et al., 1998; and many others). Large scale bedform generation and evolution in shallow coastal environments can also cause dynamic navigational hazards and can initiate burial or scour of objects on the seafloor (Bruun,
Studying the morphodynamics of bedforms can provide a better understanding of sediment transport pathways in nearshore regions, and help to better mitigate navigation hazards particularly in tidal inlets, which often serve as commercial shipping and recreational boating channels.

Tidal inlets are found all over the world's coastline and provide an important connection between the ocean and protected back-barrier areas, including estuaries, harbors, and river mouths. There is often significant exchange of fresh and salt water, nutrients, sediment, and other natural or anthropogenic particulate material (e.g., Komar, 1996). Tidal inlets provide an important ecological link between the ocean and estuaries, regions which are utilized by many organisms for benthic habitat, feeding, reproduction, and spawning (Dexter, 1947). Tidal inlets are an important economic resource as well, serving as the connection between the open-ocean and shipping ports.

Hydrodynamic flow through an inlet is controlled by a combination of tidal, wave, and wind-driven currents, and riverine (fresh water) outflow (e.g., Hayes, 1980). In inlets dominated by tidal currents, the prevailing flow direction changes with each tidal cycle (semi-diurnal or diurnal in nature), and the seafloor is commonly characterized by the presence of regular bedforms. Patterns of regular bedforms suggest a strong link between tidal currents and the evolution of seafloor morphology.

Shallow water bedforms can be detected both optically and acoustically. Historical observations of bedform patterns in inlet regions have come from aerial photographs. If aerial images are taking during low tide and/or clear water conditions, the general position of large scale bedforms are optically visible when viewed from
above. For example, seafloor bedforms in Hampton Harbor Inlet are visible in aerial images dating back to the 1970's, and are discussed later.

Developments in acoustic seafloor imaging techniques from single and multi-beam echosounders (MBES) have improved the accuracy and resolution of small to large scale bedform mapping, ranging from tens of centimeters to several hundred meters in scale. Several studies have been conducted in coastal waters and inlets that utilize high resolution MBES sonar to map bedform fields (Passchier and Kleinhans, 2005; Balouin, et al., 2004; and Cuadrado and Gomez, 2011). However, these studies have poor temporal resolution, generally comparing consecutive surveys that were obtained months or even years apart. Other studies (e.g., Whitmeyer and FitzGerald, 2008) examined weekly surveys over a bedform field, but were limited by lower spatial resolution of a single-beam echo sounder.

In this work, multiple high-resolution MBES surveys were obtained in the navigation channel of a tidally modulated inlet. Nine MBES surveys were conducted over a four-week period in the fall of 2011 at Hampton Harbor Inlet in southeastern New Hampshire in the Gulf of Maine. The surveys have horizontal spatial resolution of 0.25 m and vertical resolution of 0.1 m so that both medium scale sand dunes and small scale mega-ripple bedform features are resolved. Mean current profiles within the inlet were measured over the same study period using a mobile personal watercraft that transited the inlet, and are described in detail in Chapter 3 of this thesis. The combination of coincident high resolution bathymetry surveys with coincident observation of mean currents collected on an approximate bi-weekly time scale provides a unique dataset to examine how bedforms evolve over the course of a fortnightly tidal cycle.
The following sections describe the regional setting of the observations, and present the field and analysis methods for quantifying bedform evolution. The results focus on bedform migration in context of the general changes in mean flow patterns that vary with the fortnightly tides. The results in terms of potential sources of error and in context of other studies are discussed, and then conclusions are summarized.

2.3 Regional Setting

The inlet leading to Hampton Harbor, located within the Gulf of Maine in southeastern New Hampshire (Figure 2-1), is heavily trafficked by commercial fisherman, tourist companies, and private boaters. The inlet separates Hampton Beach to the north from Seabrook Beach to the south. Hampton Beach and Seabrook Beach are part of a barrier island system that stretches from Cape Ann, Massachusetts to Great Boars Head in New Hampshire, a reach of about 30 km. The coastal region is highly developed and the beaches are reinforced by a variety of hard structures. The beaches are also occasionally nourished with sand from borrow sites and dredge spoils from inside harbors (Kedzierski, 1993). In addition to the development and man-made alterations of the beaches, there are well developed natural dunes and large back-barrier salt marshes associated with the barriers. Sediment along the New England barrier beach system comes from a combination of inland, offshore, and updrift source areas. Large deposits of sediment are stored offshore in submerged deltas and drumlins that developed from glacial outwash during the Pleistocene. These deposits may be an important source of offshore sediment to New England beaches (Fitzgerald and Van Heteren, 1999).

The Hampton Harbor Inlet connects Hampton Harbor to the Gulf of Maine. A drawbridge marks the approximate transition from the inlet to the backbay. The main
inlet channel is about 300 m wide and about 1000 m in the along channel direction, extending from the drawbridge to approximately 250 m beyond the end of a stone jetty to the north. A stone jetty also reinforces the inlet to the south. Freshwater flow into Hampton Harbor comes from Tide Mill Creek to the north, Taylor and Hampton Falls Rivers from the northwest, Brown’s River and Cain’s Brook from the west, and the Blackwater and Little Rivers from the south (Eberhardt and Burdick, 2009). The total input of freshwater in the estuary system is estimated to be $0.19 \times 10^6 \text{m}^3/d$ (77.84 cfs), or less than 1% of the total tidal prism (Trowbridge, 2007), and is believed to have a negligible effect on sediment transport in the inlet channel.

The average spring tidal range at Hampton Harbor Inlet is 4 m, and the average neap tidal range is 2 m. The tidal currents increase during spring tides to accommodate the increased water exchange between the ocean and harbor. Currents in the inlet are typically strong and were observed to reach 1.5 m/s (discussed in Chapter 3). During the study period, the shallowest depth within the navigation channel was 2.5 m below mean sea level, while the average depth of the inlet outside of the navigation channel is less than 1 m below mean sea level and exposed at low tides. There are large, approximately 16 m deep, scour holes just seaward of the bridge pilings observed in our surveys that will not be considered in the following analysis.

Historical records show that the inlet and the barrier beach system shifted significantly over an 80 year period between 1855 and 1931, (Figure 2-2; Randall, 1989). In the 1930’s the inlet was reinforced with two stone jetties at the north and south of the inlet entrance. In 1965 the north jetty was extended by approximately 300 m, and a 100 m wide federal navigation channel was first dredged.
Figure 2-1. Map of the area encompassing the field site in the southern end of the Gulf of Maine along the New Hampshire coastline. The white outline encompasses the field study area (shown in detail at the right). The location of the directional Jeffrey’s Ledge Waverider Buoy, deployed at a depth of 73 m, 46 km offshore, is also indicated.
The inlet-navigation channel is maintained by the USACE, with a controlling depth of \(~2.4\) m (8 ft) MLLW, and needs to be dredged regularly, removing roughly 20,000 cubic yards of sediment every 5 years (PDA, 2012). Between 1965 and 1987 thirteen dredging events removed 259,263 cubic yards of material from the federal navigation channel (Kedzierski, 1993). The navigation channel was last dredged in 2005 and again in 2013 (PDA, 2012).

Figure 2-2. Historical shoreline and inlet change at Hampton, NH. Map by Alex Wallach (Randall, 1989).
Despite regular dredging of the Hampton Harbor Inlet, observations from aerial photographs of the inlet dating back to 1978 show clearly defined, large scale seafloor bedforms with wavelengths on the order of 20-40 m. Photos collected during low tide and/or when the water was clear, visibly show the presence of several large sand dune features in the inlet and navigation channel. Bedform crests were digitized from ortho-rectified aerial images in ArcGIS version 10.1 (Figure 2-3). Aerial images of the inlet from 1978, 1986, 1998, and 2000 were obtained from the USACE, Sewell Achieves, New Hampshire Coastal Program (NHCP), and National Oceanic and Atmospheric Administration - National Geodetic Survey (NOAA-NGS), respectively. The accuracy of defining crest locations from these images is not known, but shallow water aerial photography has been shown to have horizontal resolutions of 1-10 m in the context of defining habitat classification features (Alevizos, 2012; Kenny et al. 2003). The 2011 bedforms are digitized from the 17 October, 2011 multibeam survey, described later. The bedforms are common and found throughout the length and width of the inlet, extending into the navigation channel. It should be noted that deeper bedforms are more difficult to identify in aerial photography, particularly in the navigation channel. A series of monthly aerial images of the inlet were collected by the USACE in 2004 and 2005, are discussed later.
Figure 2-3. Bedform crests digitized from historical aerial images. Aerial images were obtained from the US Army Corps of Engineers (1978), Sewell Achieves (1986), New Hampshire Coastal Program (1998), and NOAA (2000). The 2011 results are from the 17 October multibeam survey. Note that the crests extend north of the inlet navigation channel. Only a few of the images were clear enough to see the bedforms extending across the navigation channel.
Chute and Nichols (1941) suggested that Hampton Beach and Seabrook Beach are neither losing nor gaining sand from areas to the north and south. However, shortly thereafter in 1947 a seawall was built at the south end of Hampton Beach (Holman, 2013). Unfortunately, hard structures, like seawalls, often contribute to erosion (e.g., Tait and Griggs, 1991), and by 1953 the USACE reported that loss of material from Hampton Beach exceeded the rate of supply (Tuttle, 1960). In 1955, the seawall was extended armoring the entire length of Hampton Beach (Holman, 2013). Later that year, the beach was artificially nourished with 700,000 cubic yards of fill (pumped from Hampton Harbor onto the beach), adding over 1,800 m to the length of the beach and doubling the width in front of the seawall (Tuttle, 1960). Sand is still occasionally trucked into Hampton Beach to maintain the beach (PDA, 2012).

As the dominant longshore drift is from north to south, the north jetty acts as a groin trapping sediment and results in a buildup of sand at the southern end of Hampton Beach. According to the PDA (2012) NH Dredge Report, the area between the southern jetty and the shoreline was back-filled with dredge spoils to act as shoreline stabilization for the community of homes that border the southern boundary of the inlet, yet most of the sediment deposited for shoreline stabilization has been removed by tidal currents and the porous nature of the stone jetty.

Offshore waves are effectively restricted in the inlet itself by waves breaking on the ebb tidal delta shoals, blocking by the north jetty, and refraction towards the south at the inlet mouth. Wave amplitudes inside the inlet are observed to be greatly attenuated (particularly at low tide stages) and do not generally affect navigation into and out of the main channel.
2.4 Field Methods

A four-week long field experiment was conducted at Hampton Harbor Inlet in the fall of 2011. A series of nine high-resolution MBES surveys were conducted in the main inlet-navigation channel. This section describes the MBES surveys and processing methods, bedform analysis procedures, and ancillary data collection, (which includes bottom-mounted ADCP measurements, offshore wave observations, and sediment sampling).

2.4.1 Multibeam Surveys

Bathymetry data was acquired aboard the R/V Coastal Surveyor, a 12 m survey vessel owned and operated by the Center for Coastal and Ocean Mapping/Joint Hydrographic Center at the University of New Hampshire. Seven days of MBES surveys of the inlet channel were conducted over a twenty-six day period from 21 September through 17 October. Three successive surveys occurring over a twelve-hour period were conducted in the inlet channel on 5 October. Surveys were also conducted offshore of the inlet, but are not considered in this study.

A 260 kHz Imagenex Delta-T 837 MBES was used to collect the high resolution depth soundings. The Imagenex Delta-T is a single head multibeam transducer with 480 beams and a 120 deg horizontal beam width. The multibeam was attached to a ram mounted on the bow of the vessel. Data was recorded using software provided by Imagenex Technology Corp. Vessel motion data, including position, heading, speed, and attitude were recorded using an Applanix POS-MV 320 v. 5.1 Inertial Measurement Unit (IMU). A GPS base station was located nearby in the township of Hampton Beach, NH (Figure 2-4), and Real Time Kinematic (RTK) position corrections were continuously
broadcast to the survey vessel. Positioning aboard the R/V Coastal Surveyor was achieved to an accuracy of about 0.05 m. Sound speed profiles were obtained hourly during each survey with a Digibar Pro Velocimeter, which has a sound speed accuracy of 0.3 m/sec. Casts were collected near the inlet mouth, by the end of the north jetty. Casts were not taken near the bridge because of the strong currents and eddies near the bridge pilings.

Figure 2-4. Overview of the survey area. A composite image of all the multibeam surveys conducted is superimposed over an aerial image (ESRI). The locations of the ADCP’s, Aquadopp, GPS base station, wind station, and sediment sample locations are also shown.
Individual MBES surveys of the inlet channel were conducted on 21, 26, 28, and 30 September, and 3, 5, and 17 October. Surveys were conducted over a 2-3 hr period at high tide except on 5 October when three successive surveys were conducted between 07:00-09:00 hrs (rising high tide), 09:00-11:00 hrs (falling high tide), and 17:00-19:00 hrs (second rising high tide). At least two full passes of the inlet channel were made during each survey. A series of 10 equally spaced (by 10 m) survey lines oriented along the long-axis of the inlet channel were transited each pass. Gaps in the surveys were sometimes unavoidable due to off-track navigation and strong currents, (particularly on 28 September). Elevations were referenced to the WGS84 ellipsoid and later re-projected to the NAVD88 vertical datum.

Vessel motion data was processed using Applanix’s POSPac software. POSPac uses real-time vessel motion measurements and a network of Continuously Operating Reference Stations (CORS), maintained by NOAA-NGS, to post-process the survey data. Attitude and position data was referenced to the WGS-84 ellipsoid and transformed to orthometric heights (relative to the NAVD88 vertical datum) using the NGS 2003 Geoid model. The NOAA Tidal Station 8423898 (Fort Point, New Castle, New Hampshire), located approximately 20 km north of the inlet, shows that mean sea level is about 9 cm above the NAVD88 vertical datum.

Survey data, including depth soundings, motion and position measurements, and sound speed profiles, were processed using Caris HIPS version 7.1. Individual soundings from all passes of a survey were processed together to establish a best estimate of seafloor topography over the 2-3 hr survey period. Inclusion of multiple passes along each survey line resulted in fewer data gaps and higher confidence in the depth
soundings. Bathymetry was gridded to 0.25 m horizontal resolution using the CUBE uncertainty analysis, which provides an estimate of seafloor depth at each grid cell based on a statistical analysis of sounding density and survey uncertainty (Calder and Mayer, 2003).

Bathymetric grids, referenced to the WGS84 ellipsoid were vertically re-projected into NAVD88 using NOAA-NGS Intg software, and the 2003 Geoid model. Bathymetry was subsequently rotated by 22 deg into a local coordinate system with origin located near the Hampton-Seabrook Bridge at coordinates 42° 53' 45.0162" N, 70° 48' 58.0644" W. The bathymetry of interest lies between 100 to 900 min the along-channel direction where prominent bedform features are present within the inlet navigation channel. Bathymetric difference plots and profiles are analyzed later in this local reference frame. An analysis of survey specific total propagated uncertainty and an acoustic uncertainty model for the Imagenex Delta-T are presented in Appendix A and Appendix B.

2.4.2 Bedform Analysis Procedures

Observed seafloor bedforms are separated by scale (wavelength and amplitude) through filtering operations performed in the wavenumber domain. Larger scale bedforms, consistent in character with large subaqueous sand dunes described by Ashley, 1990, are detected by first filtering out finer-scale wavelength features with wavenumbers above 0.08 m⁻¹. Similarly, finer scale bedforms, consistent in character with mega-ripples described by Fredsøe and Deigaard, 1992, are examined by removing the features with wavenumbers between 0.08 m⁻¹ and 0.01 m⁻¹. The filtering operations were carried out in the wavenumber domain by first filling gaps in the bathymetric grids with the average depth values along any particular along-inlet transect. A Fast Fourier Transform (FFT) was performed on each along inlet transect and then low pass filtered (in the case of the
sand wave analysis) or high pass filtered (in the case of the mega-ripple analysis) by removing wavenumbers above or below 0.08 m⁻¹. An inverse FFT of the filtered Fourier coefficients transformed features back to the space domain. Data gaps were reintroduced into the filtered bathymetric grid and a spatial buffer six pixels (1.5 m) wide was applied around the perimeter of the gaps and the entire region to avoid spurious effects of the filter at the edges of the good data regions. Profiles between the filtered and unfiltered data were compared qualitatively to ensure analysis was not obviously biased.

Bedforms, particularly sand dunes and sand waves, are traditionally analyzed by defining and mapping dominant bedform crests (e.g. Whitmeyer and FitzGerald, 2008; Cuadrado and Gomez, 2011). In this study, the positions of the larger scale sand dunes were quantitatively mapped using a fingerprint detection algorithm, henceforth referenced as the BISHNU algorithm (Bishnu, et al., 2002). The BISHNU algorithm was modified to identify coherent bedform crests and troughs from high-resolution bathymetric surfaces. The modified algorithm uses a topographic relationship between bordering pixels in a gray scale image of bathymetry to classify ridge crests and troughs. The modified BISHNU algorithm is applied to a binary image produced from a bathymetric grid and selects a series of pixels over which the bedform crests and troughs are located. The algorithm requires user-defined scale parameters that are tuned to the particular data being analyzed, and often results in additional, spurious or incomplete selection of crest and trough locations. For a detailed description of the BISHNU algorithm used in this study see Felzenberg (2009). The technique of using neighboring grid data to automatically classify topographical features is commonly used for other
geosciences applications, such as hydrologic-drainage analysis (e.g., Martz and Garbrecht, 1999; Tribe, 1992; Jenson and Trautwein, 1987).

In this work, the array of pixels representing crests and troughs – determined by applying the modified BISHNU algorithm to the low-pass filtered bathymetry – was used to manually identify single-pixel lines that represent the continuous crest and trough positions of each sand dune, figure 2-5. Uncertainties in this user-defined step are estimated to be within 1-2 pixels, or about 0.25-0.5 m. Crests and troughs of individual sand dunes were numbered, CR1 through CR8 and TR1 through TR8, for reference and subsequently compared between successive surveys to determine sand dune crest migration distances and rates.

Figure 2-5. Grayscale image of 17 October bathymetry with the pixels representing topographic highs, identified by the modified BISHNU algorithm, shown in black dots. The red lines show the manually identified single-pixel lines representing the continuous crest.

Crest positions, in particular, are sensitive to subtle topographic changes and irregularities associated with sand dune shape. The precise crest and trough positions,
although objectively determined, may not represent the overall shape of the three-dimensional bedform. To better characterize the net movement of the entire bedform, differences between successive surveys were used to identify integrated sediment volume changes in the navigation channel. Difference plots were created in Matlab by subtracting two bathymetric surfaces from one another. The difference plots represent the net migration of sediment, and are not reliant on specific locations of bedform crests or troughs.

Finer scale seafloor bedforms, typical of mega-ripples with wavelengths on the order of 1-10 m (Fredsøe and Deigaard, 1992) were observed throughout the inlet. Evolution of these bedforms generally occur at time scales much faster (order hours) than the repetition time of successive surveys (conducted on order 2-4 days). Thus, these features were grossly characterized using estimates of seafloor roughness, again using spectral analysis. The high-pass filtered bathymetric grid was divided into 50% overlapping boxes 50 m by 18 m in the along and across inlet directions, respectively. In this manner, each box region contained 72 along inlet transects, each of 50 m length. A Hanning window was applied to each mean-corrected profile along each line, and a wavenumber spectrum completed. All the spectra from the 72 lines were ensemble-averaged to yield smooth spectra with 144 degrees of freedom for each delimited box. Root-mean-square (rms) amplitudes, $A_{rms,j}$, of the mega-ripples were determined for each box $j$ by

$$A_{rms,j} = \sqrt{8 \sum_{k=1}^{k_2} S_j dk}$$

(2.1)
where $S_j$ is the ensemble averaged spectra for box $j$, $dk$ is the fundamental wavenumber, and $k_1$ and $k_2$ are the wavenumber limits of interest. The wavenumber limits were determined by cutoff wavelengths of 5 and 10 m for the larger scale mega-ripples, and 1 and 5 m for the smaller scale mega-ripples. Additionally the noise floor, essentially quantifying the resolving capability of the overall bathymetric survey (including all sources of error), was also calculated by,

$$\text{std}_{\text{noise}} = \sqrt{\frac{\hat{S}}{2\Delta}}$$

(2.2)

where $\hat{S}$ is the average spectra between wavenumbers bounded by $1 \text{ m}^{-1}$ and the Nyquist ($2 \text{ m}^{-1}$), defining the portion of the spectra where the values flatten, and $\Delta$ is the grid resolution (equal to 0.25 m). Contour plots of $A_{\text{rms}}$ and $\text{std}_{\text{noise}}$ were created from the arrays determined by the boxes.

2.4.3 Ancillary Data

Grab samples of bottom sediments were taken at four locations in the inlet. The samples were taken with a Shipek grab sampler lowered over the side of the vessel, and the positions were recorded using the shipboard autonomous GPS. Sample 4 was taken at the end of the navigation channel, approximately 250 m from the end of the north jetty. Sample 5, 6, and 7 were all taken onshore of the end of the north jetty from within the navigation channel (Figure 2-4). The samples were processed according to protocol established by the American Society of Testing and Materials (ASTM), Designation DL 6913-04 (2009), Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. The samples were oven-dried, weighed, and then sorted using a mechanical shaker and a standard sieve set ranging 0.04 to 50.8 mm (Table 2-1).
The weight of sediment in each sample was recorded and a weight percent for each sieve size computed (Figure 2-6). Sediments were predominantly medium-to-coarse grained with some larger pebbles present in some of the samples. The median grain size of all the samples from within the navigation channel was 0.85 mm, or coarse grained sand. Not surprisingly, there was a higher concentration of pebbles inside the inlet navigation channel closer to the bridge pilings, where, anecdotally, currents are very strong.

Table 2-1. Sieve sizes used in sediment analysis.

<table>
<thead>
<tr>
<th>Grain Size (mm)</th>
<th>Phi #</th>
<th>Sieve #</th>
<th>Wentworth size class</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.80</td>
<td>-5.7</td>
<td>2&quot;</td>
<td>Pebble</td>
</tr>
<tr>
<td>38.10</td>
<td>-5.2</td>
<td>1 ½&quot;</td>
<td>Pebble</td>
</tr>
<tr>
<td>24.50</td>
<td>-4.7</td>
<td>1&quot;</td>
<td>Pebble</td>
</tr>
<tr>
<td>19.000</td>
<td>-4.2</td>
<td>3/4&quot;</td>
<td>Pebble</td>
</tr>
<tr>
<td>9.500</td>
<td>-3.2</td>
<td>3/8&quot;</td>
<td>Pebble</td>
</tr>
<tr>
<td>4.750</td>
<td>-2.2</td>
<td>4</td>
<td>Pebble</td>
</tr>
<tr>
<td>2.000</td>
<td>-1.0</td>
<td>10</td>
<td>Granule</td>
</tr>
<tr>
<td>0.850</td>
<td>0.2</td>
<td>20</td>
<td>Coarse sand</td>
</tr>
<tr>
<td>0.425</td>
<td>1.2</td>
<td>40</td>
<td>Medium sand</td>
</tr>
<tr>
<td>0.250</td>
<td>2.0</td>
<td>60</td>
<td>Medium sand</td>
</tr>
<tr>
<td>0.150</td>
<td>2.7</td>
<td>100</td>
<td>Fine sand</td>
</tr>
<tr>
<td>0.106</td>
<td>3.2</td>
<td>140</td>
<td>Very fine sand</td>
</tr>
<tr>
<td>0.075</td>
<td>3.7</td>
<td>200</td>
<td>Very fine sand</td>
</tr>
<tr>
<td>0.040</td>
<td>4.6</td>
<td>finer</td>
<td>Silt</td>
</tr>
</tbody>
</table>
Figure 2-6. PDF weight percent plots on a semi-log x scale for sediment samples within the inlet navigation channel. The median grain size is 0.85 mm. Sample 4 is located farthest offshore, and sample 7 is located nearest to the drawbridge.
Two bottom-mounted RDI Workhorse acoustic Doppler current profilers (ADCP’s) were located offshore of the inlet in 12.5 m and 7.5 m depths, and one bottom-mounted 1 mHz Nortek Aquadopp ADCP was located in 2.5 m water depth on the flank of the inlet, just to the south of the inlet-navigation channel (Figure 2-4). Each profiler recorded bottom pressure which was used for observing wave conditions. The ADCP’s are explained in detail in Lippmann, et al., 2013.

Offshore wave height and direction data from the MKIII Datawell Directional Waverider Buoy Station 44098, located 46 km offshore of Hampton, NH in 73 m of water (Figure 2-1), was obtained from the Coastal Data Information Program. Wave heights and period were also obtained from the ADCP measurements (summarized in Figure 2-7). Wave conditions were variable throughout the experiment, with offshore rms wave heights ranging from 0.25 m to 1.8 m and typical periods ranging from high frequency seas (5-7 s) to long period swells (10-12 s). As waves approached the inlet mouth, they broke on the ebb tidal shoals and refracted around the jetties. Therefore, wave conditions inside the inlet were much milder due to attenuation and refraction. Wave heights recorded at the inshore ADCP show rms values ranging 0.05-0.20 m during high tides and larger offshore waves. Waves generally came out of the south-east with a few events from the north-east.

Five-hour averaged wind speed and direction, at an elevation of 12 m above sea level, were acquired at the Yankee Fisherman Coop Weather Station KNHSEABR3 in Seabrook, NH from Weather Underground (Figure 2-4). Winds during the experiment were highly variable, ranging in magnitude from 0 to 15 m/s and originating from any
particular direction determined by the passage of several meteorological frontal systems (Figure 2-7).

Figure 2-7. Environmental conditions during the study period. Water elevations (relative to MSL) were taken with a pressure sensor at the 12.5 m ADCP site. The periods of the MBES bathymetric surveys are shown with red markers. Wave height and period from the directional Waverider Buoy is shown in blue, and three bottom-mounted current profilers are shown in red (12.5 m), green (7.5 m), and black (2.5 m) in the second and third panels. Hourly averaged winds were observed at the Yankee Fisherman Coop in Seabrook, NH at an elevation of 12 m above mean sea level.

2.5 Results

First on analysis of the larger scale sand dunes, in particular bedform migrations relative to the spring and neap tidal cycles is performed. Second an analysis of the seafloor roughness elements, including spatial and temporal variability, and the noise floor of the bathymetry data is examined.
All the processed bathymetry presented in this section is gridded to 0.25 m horizontal resolution and rotated into the local coordinate system. The coordinate system has origin near the center of the bridge, and the x and y coordinates oriented along and across the channel, respectively. The area of interest in the channel is between y = 100 to 900 m from the origin, ignoring the 16 m deep scour holes just seaward of the bridge pilings.

2.5.1 Sand Dune Evolution

The bathymetry from 17 October 2011 is shown in figure 2-8. Depths ranged from 2.5 m to 7.5 m below NAVD88, (approximately mean sea level). Sand dunes, similar to those observed in aerial photography (discussed previously) are observed within the inlet navigation channel. Eight large sand dune features with crests oriented approximately cross-channel, are located between 200 m to 700 m along the x-axis, with amplitudes of roughly 1-2 m and wavelengths of roughly 20-40 m. For reference, the end of the north jetty is located at 700 m. Long-crested mega-ripples, also oriented across-channel, are present throughout the inlet channel and superimposed on the larger sand dunes. The mega-ripples range in size from 0.1-0.4 m in amplitude and 1-10 m in wavelength and are discussed later.

Figure 2-9 shows the bathymetric survey for each day (the 05 October survey conducted from 0900-1100, is shown here). The dominant features of each survey are the complex but temporally coherent fields of large amplitude sand dunes that migrate in and out of the channel.
Figure 2-8. Bathymetry surveyed on 17 October, 2011. Large sand dunes with amplitudes on the order of 1-2 m and wavelengths on the order of 20-40 m are oriented across-channel. Long-crested mega-ripples are also present throughout the flat portions of the channel as well as superimposed on top of the sand dunes. Flood tides flow from 800 m to 100 m in the along-channel direction, and ebb tides flow from 100 m to 800 m.
Figure 2-9. Bathymetry surveys for 21, 26, 28, 30 September and 03 and 05 October (0900 to 1100 survey). It is difficult to quantify changes to the bedforms from these maps.
Sand dune crests and troughs identified with the BISHNU algorithm are shown in figure 2-10. Each coherent sand dune was given an indentifying label CR1-CR8. Migration directions were estimated qualitatively, as the features are three-dimensional and often change shape and orientation over the length of the feature and between successive surveys. Crest mapping clearly shows that the net migration of each sand dune crest over the entire study period was offshore by approximately 10 to 20 m. There are interesting subtle differences between each sand dune crest. For example some sand dunes bifurcate (e.g. CR2 and CR3), and some have a more curved shape (e.g. CR1 and CR8). The migration of the sand dune crests also appear to vary spatially across the width of the inlet, for example the southern portion of sand dune CR6 migrates approximately 15 m offshore between 21 September and 17 October, while the northern portion of the same sand dune only migrates 5 m offshore.

Along channel profiles at selected cross-channel coordinates $y = +25 m$, and $y = +50 m$ are shown in figure 2-11. Each successive profile is offset vertically by -1 m from the previous survey. Crest slopes were calculated for CR2 through CR8, and given in table 2-2. The slopes are represented as positive percents, with either a "left" or "right slope", left being slopes located on the onshore side of the crest (closer to drawbridge), and the right slope being the slope located on the seaward side of the crest. CR1 does not extend up to $y = +25 m$ or $y = +50 m$, therefore CR1 slopes have not been measured.
Figure 2-10. Sand dune crests and troughs identified using the BISHNU algorithm. Crest (CR) and trough (TR) features are labeled according to a number scheme in the along channel direction. Uncertainty in crest and trough location is estimated to be 0.25 to 0.5 m in the along-channel direction.
The shape of the sand dunes are not uniform in either the across channel or along channel directions. In general, the sand dunes have asymmetrical forms varying temporally and spatially over the inlet. Some dune crests have steeper left slopes, (like CR3), while others have steeper right slopes (like CR2), while others appear symmetrical, such as CR5, see figure 2-10. In general, the sand dune slopes are steeper at the top of the sand dune (northern portion) than at the bottom (southern portion). Sand dune amplitudes range from 0.5 m (CR4), to over 2 m (CR7). The angle of repose of wet sand is approximately 45 deg. The maximum slope measured is 35 deg, the left slope of CR4 at y = 50 m on 26 September, although mean slopes are much below the angle of repose. Mega-ripples located on crests, troughs, and flatter portions of the channel are apparent on the profiles. They have amplitudes of less than 0.1 to 0.3 m and wavelengths of 1-10 m, and appear to be concentrated onshore of x = 500 m.
Figure 2-11. Along channel profiles at cross-channel coordinates \( y = 25 \) m, and \( y = 50 \) m. Each successive profile is offset by \(-1\) m from the previous survey. Dune morphology varies spatially and temporally but no clear coherent patterns with tidal cycle could be concluded from these profiles.
Table 2-2. Calculated slope values for sand dunes, CR2 to CR8. Slopes were calculated using the profiles in Figure 2-11. All slopes are represented by positive percents. The mean slope values are mean average slopes of the sand dune over the entire study period.

<table>
<thead>
<tr>
<th>50 m Profile - Left Slope</th>
<th>50 m Profile - Right Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>CR2</td>
</tr>
<tr>
<td>21 Sept</td>
<td>5</td>
</tr>
<tr>
<td>26 Sept</td>
<td>5</td>
</tr>
<tr>
<td>28 Sept</td>
<td>5</td>
</tr>
<tr>
<td>30 Sept</td>
<td>5</td>
</tr>
<tr>
<td>03 Oct</td>
<td>4</td>
</tr>
<tr>
<td>05 Oct</td>
<td>4</td>
</tr>
<tr>
<td>17 Oct</td>
<td>6</td>
</tr>
<tr>
<td>Mean Slope*</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>25 m Profile - Left Slope</th>
<th>25 m Profile - Right Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>CR2</td>
</tr>
<tr>
<td>21 Sept</td>
<td>4</td>
</tr>
<tr>
<td>26 Sept</td>
<td>5</td>
</tr>
<tr>
<td>28 Sept</td>
<td>5</td>
</tr>
<tr>
<td>30 Sept</td>
<td>4</td>
</tr>
<tr>
<td>03 Oct</td>
<td>5</td>
</tr>
<tr>
<td>05 Oct</td>
<td>4</td>
</tr>
<tr>
<td>17 Oct</td>
<td>4</td>
</tr>
<tr>
<td>Mean Slope*</td>
<td>4</td>
</tr>
</tbody>
</table>

Morphological changes to the seabed can also be shown with difference plots, which better capture the net change in sediment induced by bedform migration. The net change to inlet bathymetry over the study period is shown with a difference plot between the 21 September and 17 October surveys (Figure 2-12). The difference plot shows the integrated volume change in sediment, or the net movement of sediment over the survey period. Patterns of sediment erosion are shown in blue and deposition in red. Large, net changes are strongly evident for the large sand waves. The erosion morphology of an
individual dune closely matches the corresponding deposition pattern, showing again that the dunes remained generally coherent over the course of the experiment. Figure 2-12 shows that between 21 September to 17 October, the net migration of the sand dunes was 10-15 m offshore.

Patterns of bedform migration can be examined on a finer time scale from bathymetry differences between successive surveys. Difference plots between successive surveys are shown in figure 2-12. Positive changes in elevation, or deposition, are again shown in red, while negative changes in elevation, or erosion, are shown in blue. Arrows located in the upper right corner of each bathymetry difference plot indicate the general direction and relative rate of bedform migration. Red arrows indicate offshore bedform migration and blue arrows indicate onshore bedform migration. These bathymetry difference plots were used to estimate maximum migration rates of the net integrated volume of the bedforms. The average distance between similar sand dune features on successive surveys were qualitatively measured in Matlab and divided by the days between each survey to determine migration rates. Table 2-3 summarizes the estimated maximum sand dune migration rates relative to the tidal cycle. Observed changes in bedform amplitude are up to 1 m and closely follow the periods of neap and spring tides.

Table 2-3. Sand dune migration rates and directions. Linear migration rates are estimated from the bathymetry difference plots by dividing the maximum horizontal migration of a feature by the days between the surveys.

<table>
<thead>
<tr>
<th>Dates</th>
<th>Tidal Stage</th>
<th>Migration Direction</th>
<th>Migration Rate (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/21 to 9/26</td>
<td>Neap</td>
<td>Onshore</td>
<td>1-2</td>
</tr>
<tr>
<td>9/26 to 9/28</td>
<td>Rising Spring</td>
<td>Offshore</td>
<td>3.5-6</td>
</tr>
<tr>
<td>9/28 to 9/30</td>
<td>Peak Spring</td>
<td>Offshore</td>
<td>5-7.5</td>
</tr>
<tr>
<td>9/30 to 10/03</td>
<td>Peak Spring</td>
<td>Offshore</td>
<td>1.2-2.5</td>
</tr>
<tr>
<td>10/03 to 10/05</td>
<td>Falling Spring</td>
<td>Offshore</td>
<td>&lt;&lt; 2.5</td>
</tr>
<tr>
<td>10/05 to 10/17</td>
<td>Neap</td>
<td>Onshore</td>
<td>&lt;&lt;1</td>
</tr>
</tbody>
</table>
Figure 2-12. Difference plot between 21 September and 17 October. Depths represent changes in elevation in meters. Net migration is offshore by 10-20 m.
Figure 2-13. Difference plot between successive surveys. Depths represent changes in elevation in meters. Arrows at the top right of each plot represent migration rate between successive surveys in m/day. Red arrows represent offshore migration, and blue represent onshore migration.
Bedform migration can be subsequently related to the fortnightly tidal phases. Figure 2-14 shows the tides over the study period with arrows indicating the general direction and relative rate of bedform migration. Between 21 and 26 September the sand dunes migrate onshore approximately 1-2 m/day. From 26 to 28 September the sand dunes migrate slightly offshore during the beginning of the spring tide. The sand dunes continue to migrate offshore during the spring tide from 28 to 30 September and again from 30 September to 03 October. The largest migration rates are observed between 28 and 30 September, which corresponds to the largest observed tidal range. There is a small net offshore migration observed during the transition between spring and neap tide, occurring from 03 and 05 October. During periods of neap tide, between 05 and 17 October, the bedforms show a net onshore migration of less than 1 m/day.

Figure 2-14. Tide over the study period with the arrows from figure 2-13 indicating sand dune migration direction and rate. Bedforms migrate onshore during neap tides and offshore during spring tides. Survey dates are highlighted in pink.
2.5.2 Seafloor Roughness

In order to quantify the spatial character of smaller scale bedforms, the larger wavelength sand dunes were filtered out of the bathymetry data. An example of a filtered and unfiltered profile along $y = 50 \, m$ from the 17 October survey is shown in figure 2-15. Similar mega-ripples can be seen in the original and filtered profiles, verifying that the small scale bedform features that are superimposed on top of larger bedform features are not dampened out through filtering.

Figure 2-16 shows an example of filtered bathymetry from 30 September and an example window over which the smoothed wavenumber spectra were calculated. The bottom right shows the ensemble averaged spectra from the example window. The spectral energy decays with increased wavenumber as expected with slight increase in energy around $5 \, m$ wavelengths. Root-mean-square amplitudes, $A_{\text{rms}}$, as a function of wavenumber, are calculated from each ensemble averaged spectra using (2.1). The noise floor of $0.015 \, m$ is clearly evident at $k > 1 \, m^{-1}$, and is calculated from (2.2).

![Figure 2-15. An unfiltered and filtered (high pass filter) profile from $y = 50 \, m$. Similar mega-ripple features can be seen in both the original and filtered profiles.](image-url)
The unfiltered bathymetry, filtered bathymetry, and $A_{rms}$ contour plots for 1-5 $m$ and 5-10 $m$ wavelengths, and the noise floor contours for 30 September are shown in figure 2-16. Average noise flood contours for each survey are shown in Appendix C. $A_{rms}$ contours for the 1-5 $m$ and 5-10 $m$ wavelength features are shown in figures 2-18 and 2-19, respectively. The bottom roughness evolves as a function of both space and time, growing in aptitude from 21 to 28 September on the rising spring tide, and decaying from 28 September to 17 October, on the falling spring tide and neap tides. Mega-ripples closer to the bridge (250-500 $m$ along-channel) have greater amplitudes than those located further offshore (600-700 $m$ along-channel). There were only a limited number of mega-ripples observed between 700-800 $m$ along-channel, on the seaward end of the channel.

Changes in $A_{rms}$ amplitudes over a single tidal cycle are shown in figure 2-20. The first survey of 05 October (at 0900 hrs), was conducted during the rising high tide. The second survey (at 1100 hrs), was conducted during the height of the high tide, and the third survey (at 1700 hrs), was conducted during the second rising high tide of the day, after low tide. The 5-10 $m$ wavelength mega-ripples have greater amplitudes than the 1-5 $m$ wavelength features. The mega-ripples of both scales evolve spatially and temporally between each of the surveys.
Figure 2-16. Example box spectrum. The top plot indicates the area over which the spectrum was calculated. The bottom left plot shows the individual lines over which the one dimensional FFT was performed. The bottom right plot shows the ensemble average spectra of the area indicated in the top plot.
Figure 2-17. Mega-ripple analysis plots for 26 September. The top panel shows the unfiltered bathymetric surface (depths are in meters below mean sea level), the second panel shows the high pass filtered bathymetry (depths are relative changes in elevation in meters), the third panel shows the 1-5 m RMS amplitudes contours, the forth panel shows the 5-10 m RMS amplitudes contours, and the bottom panel shows the noise floor contours. The color bars for panels three through five are in meters.
Figure 2-18. RMS amplitude contours for the 1-5 m wavelength features. Roughness amplitudes increase during the spring tide (26, 28, 30 September) and decay during the ebb tide (21 September and 17 October).
Figure 2-19. RMS amplitude contours for the 5-10 m wavelength features. Roughness amplitudes increase during the spring tide (26, 28, 30 September) and decay during the ebb tide (21 September and 17 October).
Figure 2-20. RMS amplitude contours for the three surveys conducted on 05 October. The left plots show the 5-10 m wavelength features and the right plots are for the 1-5 m wavelength features. Megaripples exhibit slight changes in roughness both temporally and spatially between each of the surveys.
2.6 Discussion

Over the four-week study period, the dominate bedform migration was offshore with a strikingly coherent pattern of bedform migration during the fortnightly tidal cycle. Sand dunes migrate offshore during spring tides, and migrate onshore during neap tides. Sand dune migration is three-dimensional, with sand dunes that migrate horizontally at different rates along the length of the crests, change morphological shape, and grow and decay in amplitude. Bedform morphologies vary spatially throughout the inlet, and individual bedform morphologies evolve in both space and time. Several sand dunes exhibit crest asymmetry in the across-channel direction. In general, sand dune crests on the northern portion of the inlet were found to have greater amplitudes and steeper slopes.

Traditional methods of measuring bedform migration through crest mapping show how the crest of a bedform develops over space and time, however this does not necessarily represent the volume change of the bedform. The modified BISHNU algorithm provided an objective way to pick crests and troughs of the sand dunes located in the inlet navigation channel. The results of crest mapping qualitatively show how each sand dune crest varies spatially over space and time; however this method cannot provide details about how the entire three-dimensional bedform is evolving.

MBES mapping provided high-resolution bathymetry surfaces over the entire area of the navigation channel seabed, which allowed us to measure net volume change of the bedforms. Bathymetry difference plots were used to estimate two-dimensional bedform evolution and net volume changes, indicating where erosion and sedimentation was occurring between surveys. Volume changes can be used to determine patterns of sediment transport associated with bedform migration.
Smaller scale bedform features, classified as mega-ripple were resolved with the high-resolution bathymetry surveys. The mega-ripples are randomly distributed throughout the inlet, and were not observed seaward of the end of the north jetty. Bottom roughness changes, characterizing the relative amplitudes of the mega-ripples, change through space and time as a function of the fortnightly tidal cycle. The mega-ripples in both wavenumber bands analyzed in this study grow in amplitude during spring tides and decay with the neap tides. Although mega-ripple scale features were resolved, quantifying the direction of mega-ripple migration over a single daily tidal cycle was not possible with our survey methods because individual mega-ripple features could not be independently identified. Each survey took approximately 2 hours to complete, and the small scale mega-ripple features may be changing faster than this time scale.

Prior to the construction of the north jetty extensions and navigation channel in 1965, there was a large ebb tidal delta offshore of Hampton Harbor Inlet. Although there are no high-resolution hydrographic survey records from this period, aerial photos taken during low tide do not indicate the presence of any large across-channel oriented sand dune features. The first evidence of the bedforms comes from aerial photographs taken in 1974, after the formation of the jetties, perhaps indicating the influence of the jetties on the flow patterns and development of bedforms. Despite regular dredging of the Hampton Harbor Inlet navigation channel entrance, sand dune features appear to be common features of the inlet morphology.

Bedform migration observations were confined to the deeper navigation channel, yet the bedforms are known to extend beyond the confines of the channel. Future studies
to collect coincident bathymetry and mean currents over the entire width of the inlet could be used to better quantify patterns of bedform migration in Hampton Harbor Inlet.

Another limitation of this study is that only one spring/neap tidal cycle was observed. Bedform crests were digitized from aerial images of the Hampton Harbor Inlet collected on monthly intervals from 2004 and 2005 by the USACE. In this analysis only a portion of the bedforms from within the navigation channel can be seen in the aerial images. The digitized crests indicate that sand dunes migrate both onshore and offshore between October 2004 and March 2005, (Figure 2-21). Our results suggest that the sand dunes should migrate seaward (on the order of 10-15 m) each month, but this is not the case in the aerial photos. Net movement of crests is not 75 m offshore, suggesting that fortnightly conditions in current patterns must vary through time, or that other factors contribute to the net transport, such as storms.
Figure 2-21. Bedform crest migration on a monthly time scale. Crests were digitized from images taken by the US Army Corps of Engineers from October 2004 to March 2005. There appears to be a net onshore migration between October and November 2004, and onshore migration of portion of the crests in the navigation channel between February and March 2005.
This study was conducted with a relatively inexpensive multibeam sensor in very shallow water. The multibeam performed well for the purposes of this study. Averaging at least two passes of the inlet navigation channel was essential to achieve the high-resolution surveys. The outer beams of the MBES used in this study has poor range resolution, so tighter line spacing of the survey lines was necessary to ensure overlapping beams. The noise floor calculations show that the system can resolve vertical amplitudes of at least 0.05 m and on average 0.008 m on any of the survey days. The noise floor is lower during periods of calm environmental conditions. Noise floor values were the highest on 28 and 30 September (survey average of 0.01 m); days where the currents were the strongest and waves in the inlet at high tide were about 0.1 m.

The noise floor estimations and uncertainty analysis confirm that the system performed well enough to distinguish mega-ripple scale features on the seafloor, however this study could not be used to determine what direction the individual smaller scale mega-ripples migrated. Each survey took 2 hrs to complete, and there could be significant evolution of small scale features over that period of time.

Surveying could only take place during high tide stages due to the 2 m draft of the survey vessel. Observations of bedforms migration over one complete tidal cycle would further enhance the understanding of the inlet morphodynamics. Furthermore, having simultaneous current measurements would provide a complete picture of inlet dynamics. Mean current observations were collected at near coincident times as the bathymetry, but using a separate small maneuverable survey vessel, which is discussed in detail in Chapter 3. The combination of mean current measurements and high resolution
bathymetry of the entire inlet, not just the navigation channel, will provide further observations of Hampton Harbor Inlet dynamics and bedform migration.

\subsection*{2.7 Conclusions}

High resolution bathymetry surveys were collected over a fortnightly tidal cycle in the Hampton Harbor Inlet in September and October 2011. Seafloor topography from within the inlet navigation channel was measured to a horizontal resolution of 0.25 m and vertical resolution of 0.05 m using an Imagenex Delta-T MBES. Tidal elevations were measured with pressure sensors on bottom-mounted tripods. Over the fortnightly tidal cycle, sand dune morphologies vary both spatially throughout the inlet and temporally on hourly to monthly time scales. Large amplitude sand waves of up to 2 m height were observed to migrate up to 10 m over just a few days. The migration of the sand dunes was onshore during neap tides and offshore during spring tides, with the net change dominated by the spring tidal ebb-flowing currents. Although the net migration of sand dunes over the study period was offshore, some historical evidence suggests that net migration may be onshore at other times.

Analysis of mega-ripple amplitudes were used to determine roughness elements of the navigation channel. Mega-ripple rms amplitudes evolved both spatially and temporally over daily and weekly tidal cycles. Roughness elements increased during rising spring tides and decayed during falling spring tides and neap tides.

Large amplitude migrating bedforms can create dynamic navigational hazards in heavily trafficked inlets, particularly the Hampton Harbor Inlet. Having a clear understanding of seafloor morphology and patterns of migration can aid mariners as well as coastal engineers and planners. Monthly surveys conducted over a year long period,
would provide a more comprehensive picture of bedform migration in the Hampton Harbor Inlet.
CHAPTER 3

OBSERVATIONS OF MEAN CURRENTS WITHIN A TIDALLY MODULATED INLET

3.1 Abstract

Mean current observations were obtained concurrently with high resolution multibeam echosounder surveys in the strong tidally modulated Hampton Harbor Inlet over a four-week period in the fall of 2011. Current measurements were obtained with a highly maneuverable survey system, the Coastal Bathymetry Survey System (CBASS), equipped with downward-looking acoustic Doppler current profiler (ADCP). CBASS derived currents were compared with fixed, bottom-mounted upward-looking ADCP’s and found to have excellent accuracy, with root-mean-square errors of 0.03 m/s in magnitude and 15 deg in direction.

Current profiles along cross and along-inlet transects are used to quantify the gross behavior of the flow patterns as a function of tidal cycles. Observations of mean currents are categorized as being collected during either neap or spring tides, and are further separated into flooding and ebbing tidal stages. Observations show that currents accelerate into the inlet during flooding tides, and extend well offshore during ebb tides. Tidal currents within the inlet are stronger during spring tides than during neap tides.
Patterns of sediment transport are estimated from shear stress estimates, using vertical profiles of mean currents to calculate friction velocities and Shields parameters. Averaging over the same neap/spring and flood/ebb periods shows that friction velocities are higher during neap-flood tides than neap-ebb tides, and higher during spring-ebb tides than spring-flood tides. Results are consistent with the observed patterns of the sand dune migration (discussed in Chapter 2). Furthermore, friction velocities are strongest during the spring-ebb tides, also consistent with the overall net seaward migration during the four-week long experiment.

3.2 Introduction

The regularity of bedform wavelength, amplitude, and orientation suggests a strong feedback mechanism between flow and sediment transport (e.g., Gallagher, *et al.*, 1998). Improved understanding of the morphological evolution of bedforms can greatly improve sediment transport modeling and help better predict changes to seafloor topography. This is particularly important in inlets where the general morphology is determined by complex flow conditions driven by tides, surface waves, wind driven currents, and fresh water outflow (e.g., Hayes, 1980). In inlets dominated by tidal flows, the prevailing flow direction changes with each flood and ebb tide complicating the evolutionary pattern. The evolution of seafloor topography is inherently nonlinear, as current flows modify the bedforms, the bedforms in turn modify the flow field, leading to sometimes complex bathymetric irregularities that are not easily predictable.

The feedback between flow structure and bedform evolution has led to the development of a number of computer models that address seafloor topographic evolution in inlets (e.g., Hulscher, 1996; Elias, *et al.*, 2006; and many others). These
models provide a means to predict how inlet bathymetry responds to a variety of environmental forcings including water level variations, tidal currents, wind driven currents, storm waves, stratification, and changes to the sediment budget. Model accuracy is important, as models are widely used by engineers and coastal-zone managers to design structures in the nearshore, plan for dredging of navigational waterways, and define policies concerning development in and around coastal waterways (e.g., Mehta, 1996). The complexity brought on by nonlinear feedback has led some investigators to develop empirical formulations derived from field observations to make coastal evolution predictions, (e.g., Elias et al., 2006; Villard and Church, 2003; Green and Black, 1999). Despite their differences, all of these studies conclude that model accuracy will increase with more field observations to drive and validate the model algorithms, particularly large scale observations of fine-scale seafloor bathymetry and coincident flow structure.

Recent developments in multibeam echosounder (MBES) surveying techniques have allowed for more detailed and accurate mapping of fine-scale seafloor bedforms in shallow water. For example, MBES observations of fine-scale bedform evolution were obtained over a fortnightly tidal cycle in the Hampton Harbor Inlet navigation channel, located in southeastern New Hampshire, USA, and are described in detail in Chapter 2 of this thesis. In Hampton Harbor Inlet sand dunes and mega-ripples, mapped to a horizontal resolution of 0.25 m, were observed to migrate on bi-weekly time scales and over fortnightly tidal periods. Sand dunes, on the order of 1-2 m in amplitude and 20-40 m in wavelength, were observed to migrate up to 2 m/day onshore during neap tides, and up to 9 m/day offshore during spring tides. Mega-ripples, with 0.1-0.4 m amplitudes and 1-10 m wavelengths, were characterized by estimating seafloor roughness elements over
defined wavenumber ranges using spectral methods. Mega-ripples evolved spatially and temporally over the study period, and were observed to grow in rms amplitude by about 0.1 m during spring tides.

In this work, we describe observations of mean currents that were obtained in the Hampton Harbor Inlet coincident with the MBES surveys, and examine the relationship between mean flow structure and patterns of bedform migration. Mean currents in the inlet are anecdotally well known to be quite large, causing navigational hazards during peak flood and ebb tidal periods. Furthermore, average depths of the Hampton Harbor Inlet outside of the dredged navigation channel are less than 1 m at MLLW, so observations within the inlet are difficult to obtain from a moving platform and in general, cannot be surveyed using traditional survey vessels.

As part of this research, a highly maneuverable personal watercraft equipped with an ADCP was used to measure mean current profiles throughout the inlet and directly offshore on the inner shelf. Previous studies have used acoustic Doppler current profilers mounted on moving vessels to measure currents in rivers (e.g., Szupiany, et al. 2009; Szupiany, et al., 2007) and other aquatic environments with small surface waves (e.g., Sime, et al., 2007; Fong and Monismith, 2004).

Continuous current measurements were provided by continuously recording bottom-mounted ADCP’s. A comparison between the currents measured by the fixed-position ADCP’s and those measured from the personal watercraft (discussed later) show that mean current profiles are accurately measured from the small maneuverable moving platform.
Mean current profiles obtained from the CBASS were used to examine the vertical flow structure in the Hampton Harbor Inlet and estimate friction velocities and Shields parameters, (as in Szupiany, et al., 2012 for their river work). Friction velocity calculations were categorized according to tidal stage and averaged together. Tidally averaged friction velocity values were qualitatively compared to observations of coherent sand dune evolution. Results show that high resolution bathymetry surveys, along with coincident current measurements and shear velocity estimates, can be used to examine patterns of sediment transport associated with fine-scale bedform migration over a monthly time scale in a shallow tidally modulated inlet.

3.3 Methods

A field experiment was conducted at the Hampton Harbor Inlet in southeastern New Hampshire, USA, during the months of September and October, 2011 (Figure 2-1). Nine high resolution MBES bathymetry surveys of the inlet navigation channel were conducted over a four-week period. Bathymetry changes observed in the inlet were predominantly associated with the evolution of large sand dunes that migrated landward during neap tides, with 2 m tidal range, and seaward during spring tides, with 4 m tidal range. A detailed description of the study site and bathymetry surveys can be found in Chapter 2 of this thesis.

Mean current measurements were obtained with both bottom-mounted continuously recording ADCP’s, as well as on a small maneuverable survey vessel equipped with a downward looking current profiler. Vertical mean current profiles were used to estimate friction velocities and Shields parameters, which were used to predict patterns of sediment transport.
3.3.1 Current Measurements

Three ADCP's were deployed during the experiment to continuously record current measures. The instruments include two bottom-mounted RDI Workhorse ADCP's, located just outside the inlet mouth on the inner shelf in 12.5 m and 7.5 m water depths, and one bottom-mounted Nortek Aquadopp current profiler located in 2.5 m of water within the inlet, just to the south of the main navigation channel (Figure 2-4). Currents were collected continuously between 1 - 1.6 s, and averaged over time periods dependent on the CBASS transect times (discussed later). Vertical bin resolution was 0.5 m for the offshore ADCP’s and 0.2 m for the inshore current profiler. Currents averaged over 15-60 min have resolution of better than 0.01 m/s. All three current meters also collected continuous bottom pressure that was used to measure waves and water elevation changes. Details of the ADCP deployments can be found in Lippmann, et al., (2013).

Mean currents throughout the inlet were obtained along specific cross and along-inlet transects using the Coastal Bathymetric Survey System (CBASS), a GPS-based personal water-craft (12 ft Yamaha GP1200) equipped with a 1200 kHz RDI ADCP with bottom-tracking and 192 kHz single-beam echo sounder (Lippmann and Smith, 2009). Real Time Kinematic (RTK) GPS positioning was established from position corrections broadcast to the survey vessel from a base station set up in the nearby township of Hampton, NH (Figure 2-4; see Chapter 2 for details).

CBASS surveys were conducted over 3-10 hr duration on ten separate days over a 22 day period. The times of the CBASS surveys are indicated in figure 3-1 as a function of tidal elevation. The CBASS operated at speeds of 4-8 knots. Five across-channel transect lines were taken within the inlet and one along-channel transect was collected down the center of the channel during each survey (Figure 3-1). Transects were also
collected over the 12.5 m and 7.5 m ADCP’s to provide a comparison with fixed position current measurements that have high temporal resolution and accuracy.

Following guidance by Szupiany, et al. (2007), each transect line was transited ten times over a 15-60 min period, depending on the length of the transect. Time-averaged currents were calculated over 50% overlapping boxes, 30 m by 30 m, aligned with each transect. This averaging technique was used to reduce noise from surface wave orbital velocities and vessel motion (similar to Szupiany, et al., 2007). Current profiles were further averaged over adjacent vertical bins, to reduce uncertainties in the Doppler current estimates, which yielded current profiles with 0.5 m vertical resolution.
3.3.2 Shear Stress Estimates

Current velocities vary vertically between the seafloor and the free stream flow due to turbulence at the bed. The vertical current structure depends on the nature of the fluid-sediment interaction, and can be used to estimate shear velocities, or friction velocities, $u_\tau$. When the current profile is logarithmic, friction velocities characterize when sediment is entrained into the flow (Sherwood, 2006; Nielson, 1992).

Friction velocities were calculated over regions of along and cross-channel transects to determine how shear stresses vary spatially throughout the inlet, and to get a
first-order estimate of sediment transport patterns. Time-averaged currents obtained by CBASS along cross and along-inlet transects are used to estimate mean current magnitudes. An area, or interval, along each cross section was selected to analyze the vertical mean current profile and determine a friction velocity value. The intervals of the along-channel transects were set at 40 m in length, beginning at along-channel distance 300 m. The interval for the across-channel transects was qualitatively selected based on the seafloor being approximately uniform (not located along a steep slope), and in the region associated with the strongest currents. The intervals over which the across-channel transect profiles were examined ranged from 25 to 90 m along the survey transect.

Mean current magnitudes over the interval were plotted on a semi-log-y scale as a function of depth. The plots were examined visually for the presence of a log boundary layer. Bottom interference of the acoustic signal was common, sometimes corrupted the deepest current measurement. Therefore, if a boundary layer existed except for the deepest measurement, and that measurement was outside the expected uncertainty, the point was discarded and the log profile was re-evaluated. If the log profile contained a linear bottom boundary layer then friction velocity, \( u_* \), was calculated over the boundary layer following Sherwood, et al., (2006) and Huntley (1988) using

\[
    u(z) = \frac{u_*}{k} \ln \frac{z}{z_o}
\]  

(3.1)

where \( u(z) \) is the current magnitude, \( k = 0.41 \) is von Karman's constant, \( z \) is elevation above the bottom, and \( z_o \) is the hydraulic roughness length or location at which velocity is assumed to be zero (Nielson, 1992). A linear regression model was used to calculate \( u_* \) in (3.1).
The modeled \( u_* \) fit was compared with the observed mean current profile and the model skill computed by taking the variance of the modeled current profile divided by the variance of the observed mean current profile. If the skill was over 0.85, the model given by (3.1) was considered reasonable, and that \( u_* \) value was used in determining average friction velocities. All acceptable \( u_* \) measurements were averaged as a function of tidal stage, including spring-flood, spring-ebb, neap-flood, and neap-ebb.

The condition under which sediment in transported is described by the non-dimensional Shields parameter, \( \theta \), defined as the ratio of quadratic bed shear stress to the immersed weight of the mean sediment grains,

\[
\theta = \frac{\rho u_*^2}{g(\rho_s - \rho)d_{50}}
\]  

(3.2)

where \( \rho \) is the density of water, \( \rho_s \) is the density of the sedimentary material (in our case, quartz), \( g \) is gravity, and \( d_{50} \) is the median diameter grain size of the sediment (Shields, 1936). The critical Shields parameter, \( \theta_c \), defines a threshold used to determine when incipient motion of a sediment grain will occur under a given set of hydrodynamic conditions. If the Shields parameter is greater than the critical Shields parameter then sediment transport is initiated. The critical Shields parameter is defined by equation 3.2, using the critical friction velocity due to friction acting on the bed. The critical Shields parameter for this study was determined using the empirical Shields diagram that relates \( \theta_c \) to the Reynolds number, \( Re \), of a particle, and was established through experimental observations of incipient motion of sediment grains (Fredsøe and Deigaard, 1992). A
minimum and maximum Reynolds number were calculated using the minimum and
maximum $u_*$ values of the experiment and the equation,

$$ Re = \frac{u_* d_{50}}{\nu} $$

(3.3)

where $\nu = 1.18 \text{ m}^2/\text{s} \times 10^{-6}$, the kinematic viscosity of water with salinity equal to 32 ppt,
and temperature equal to 15 deg C. Through this method, $\theta_c$ was estimated to range from
0.04 to 0.055. A second, similar critical Shields parameter of 0.05 was also estimated
using the Madsen-Grant diagram, which uses $d\sqrt{(s-1)gd/4\nu}$ as the horizontal component rather than the Reynolds number (Madsen and Grant, 1976).

To determine the mode of sediment transport the Rouse parameter, $R_o$, or the ratio
of settling velocity to friction velocity, was calculated using,

$$ R_o = \frac{\omega_s}{k* u_*} $$

(3.4)

where $\omega_s$ is the settling velocity for sediment with a grain size of 0.85 mm. The drag law
was used to calculate a settling velocity of 0.098 m/s (Fredsøe and Deigaard, 1992). The
mean friction velocity values, categorized according to tidal stage, were used to calculate
a Rouse parameter for each of the four tidal stage categories.

3.4 Results

Results are presented in three sections. The first describes environmental
conditions encountered over the duration of the experiment. Secondly, the accuracies of
the CBASS measured current profiles and mean current measurements from within the
inlet are examined. Lastly, estimates of sediment transport parameters are discussed.
3.4.1 Environmental Conditions

Figure 3-2 shows the general conditions encountered during the field experiment as a function of tidal phase and elevation. Wave heights were generally mild with offshore significant wave heights around 0.2 – 0.5 m during much of the experiment. Offshore significant wave heights exceeded 1.8 m during the occurrence of two storms events. Waves are strongly attenuated within the inlet owing to waves breaking on the ebb tidal shoals and refraction away from the inlet mouth. Waves varied from locally generated seas with 5-7 s mean periods to longer crested swells with 10-11 s mean periods, and were generally out of the southeast with changes owing to several frontal systems that passed the field site. Winds were variable owing to the frontal systems and did drive a surface flow on the inner shelf that modified the offshore current structure (Lippmann, et al., 2013). Within the inlet, the winds had little effect owing to the narrowness and the generally sheltered nature of the inlet channel. Fresh water inflow to the inlet was negligible during the experiment owing to low flow streams entering the Hampton Harbor estuary. A lack of stratification was also observed from the CTD casts (Chapter 2 and Appendix B). The water column within the inlet channel is well mixed, and dominated by exchange at the mouth of the inlet.
3.4.2 Mean Currents

First the accuracies of the CBASS measured current profiles are examined. Figure 3-3 shows an example of the current magnitude and direction (relative to true north) measured by the CBASS along line 10 (see Figure 3-1 for location of transects). The coordinates along the line have arbitrary origin determined by the end point of the transect line. Line 10 passes directly over the ADCP located in 12.5 m water depth and its position is indicated in the figure with the dashed vertical lines. Currents along this transect were measured during an ebb tide over of period of 50 min on 26 September. The velocity structure shows strong vertical and horizontal variation, a result of the
interaction between the strong inertial ebb-tidal current exiting the inlet, the tidally driven
flow on the inner shelf, and any wind-driven flows that may be present (Lippmann, et al.,
2013). Current magnitudes range from about 0.5 m/s near the surface to near zero at the
bed. Current directions vary strongly over the vertical with the flow in the upper part of
the water column heading nearly directly offshore, whereas the sub surface flow in the
lower half of the water column rotates about 90 deg to the north.

A comparison between the CBASS-derived current magnitude and direction and
the bottom-mounted ADCP is also shown in figure 3-3 as a function of NAVD88
elevation. The location of mean sea level during the survey and the sea bed is shown
with the horizontal dashed lines. The comparison is very good with the CBASS currents
accurately capturing the flow structure and rotation. Side lobe interference at the bed can
be problematic owing to the pitch and roll of the CBASS during data collection, and its
effects are evident in the example by the spurious direction of the bin closest to the
bottom. These data points can be easily filtered and ignored.

Figure 3-4 shows currents obtained along transect 8 located in shallower water on
the edge of the inner shelf just seaward of the inlet mouth (Figure 3-1). These currents
were measured on an ebb tide on 28 September. The flows at this location have high
horizontal variability, clearly showing the location of the ebb-tidal jet with surface
currents of about 1.25 m/s. The lateral shear in this current is quite strong, with weak,
near zero flow within 200 m to the north and south. The location of the bottom-mounted
ADCP is indicated with the vertical dashed line. A comparison of the currents observed
with the CBASS and the fixed instrument is shown in figure 3-4, and again shows good
agreement capturing the vertical structure of the flow.
Figure 3-3. Current magnitude and direction along line 10. The dashed line represents the location of the bottom-mounted ADCP. The plots to the right represent magnitude and direction measured by the CBASS, in blue, and bottom-mounted ADCP, in red.
Overall, 10 transects were conducted over the two ADCP's during the experiment. Data were filtered based on averaging time being at least 15 min, and eliminating obvious spurious data near the bed from side-lobe interference. Figure 3-5 shows a comparison between all filtered data recorded by the CBASS and bottom-mounted ADCP's. The correlation, $R$, is high with $R^2 = 0.97$ for the magnitude, and $R^2 = 0.96$ for the directions. The best fit regression slope is shown in each figure, with slopes of 1.00 and 1.03 and y-intercepts of 0.01 m/s and -6.0 deg for magnitude and direction, respectively. Calculated rms errors are 4.5 cm/s in magnitude and 17 deg in direction. The confidence in magnitude is much higher than direction owing to the accuracies in using bottom-tracking and tilt sensors to remove vessel speeds from the data. Results show that mean currents obtained with the CBASS can be used to accurately resolve the vertical structure in flow velocities for estimating logarithmic profiles and friction velocities.
Observations of MBES surveys (Chapter 2) show that observed sand dunes in the inlet migrate onshore during neap tidal cycles, when tidal amplitudes are 1 m, and offshore during spring tides, when tidal amplitudes are 2 m. To examine the gross, qualitative relationship between sand dune migration and flows in the inlet, currents were measured along the main inlet transect (line 11 in Figure 3-1) periodically during the experiment (Figure 3-2). Currents were separated based on their sampling times, occurring during spring-flood, spring-ebb, neap-flood, or neap-ebb, and then averaged. All current elevations are converted to NAVD88 vertical datum and contoured as a
function of distance along transect line 11 (Figure 3-6). Just outside the inlet mouth (located at along-transect coordinate 700 m at the end of the north jetty, Figure 2-2) flood tidal currents are similar in magnitude on both spring and neap tides with observed currents of about 0.5 m/s. As currents enter the inlet, they accelerate rapidly with observed flows exceeding 1.0 m/s and 1.5 m/s during neap and spring periods. Larger flows during spring tides occur in the inlet because of the larger pressure gradient at the mouth. On ebb tides, the currents extend much further offshore, well beyond the end of the north jetty at the inlet entrance. Not surprisingly, currents are much stronger during spring tides when the tidal prism within the estuary is significantly larger.

Figure 3-6. Average current magnitudes according to tidal stage. Magnitudes are represented in m/s.
3.4.3 Shear Stress Estimates

Observations of the vertical current profiles throughout the inlet were used to calculate friction velocities and Shields parameters (described earlier). As an illustration of the vertical structure of the current field, an example cross-inlet current transect from line 4 on 28 September during spring-flood tides is shown in figure 3-7. The currents have magnitudes exceeding 1.5 m/s. There is a horizontal gradient of the currents, with the main jet located in the center of the channel and flows to the north (left in the figure) decaying to near zero within 100 m of the main jet. Currents near the northern boundary of the inlet reverse direction forming a large circulation pattern with (weaker) outgoing flows near the jetty. Flows to the south are large right up to the shoreline, likely a consequence of the overall geometry of the inlet channel itself.

The structure in the center of the channel over the sand dunes is of particular interest. The vertical structure can be used to estimate the friction velocity by looking for logarithmic variation in the mean current profile near the bed. The current profile for line 4 on 28 September, averaged down the center of the channel over a horizontal interval of 40 m, is also shown in figure 3-7. Current magnitude in the upper half of the water column is nearly uniform, whereas in the lower half the current rapidly decreases. To estimate friction velocities using (3.1), a logarithmic curve is fit to the mean current profile using a linear regression. The current profile shown in figure 3-7 is plotted on a log scale in figure 3-8 to illustrate the logarithmic behavior of the flow in the lower half of the water column. The skill of the log fit over the lower six points in the profile is equal to 0.995. This fit is used to estimate \( u_\text{t} \), and which is indicated on the plot in figure 3-8. Profiles similar to this example are examined for all cross and along inlet current transects obtained over the 10 survey periods.
Figure 3-7. Cross section of current magnitudes and directions at line 4 from 28 September. The x-axis represents distance along the line, originating from the southern side of the inlet and crossing to the northern side. Vertical black dashed lines show the vertical structure over which friction velocity was calculated. The plot on the right shows the measured current profile with the log fit boundary layer overlaid in red.

Figure 3-8. Linear log boundary layer at line 4 for the 28 September flooding tide. A logarithmic boundary layer exists over the bottom six measurements, indicated by blue dots.
Figure 3-9 shows the current profile obtained down the center of the channel along CBASS-transect line 11, during a spring-flood tide on 28 September. The current structure is strongly modified by the large sand waves, and clearly shows horizontal variation that, in general, consists of weaker currents over the crest of the sand waves and stronger currents in between, particularly toward the ocean end of the channel (to the right in the figure). Also shown in the figure is the bathymetry measured from the MBES survey on that day, and estimates of the bed roughness for two length scales as a function of along inlet distance (described in Chapter 2). Mean current profiles averaged every 40 m along the transect are shown in the top panel. Logarithmic boundary layer profiles that fit to the observed current profiles with skill greater than 0.85 are shown in red. These log fits are retained in the analysis as acceptable representation of the bottom boundary layer and are used to estimate $u_*$. Estimated values of $u_*$ for this transect are shown in the panel with the bottom roughness. Figure 3-10 shows the same plots for 26 September, during a spring-ebb tide.
Figure 3-9 (Previous Page). Plots from 28 September Flood Tide. Top panel shows 12 current profiles equally spaced by 40 m along CBASS transect line 11. The current profiles are plotted on a log scale with the black vertical line representing the starting interval over which the currents were averaged. The second panel is the current magnitude down the center of the channel at line 11, with the multibeam bathymetry. Sand dunes are labeled according the crests numbers established in Chapter 2. The third panel shows rms amplitude values over the same region for 1-5 m and 5-10 m wavelength mega-ripples, u values are also plotted on the same scale in m/s. The bottom panel shows the original channel bathymetry with the current profile line shown in black.
Figure 3-10. Same plots as above but from the ebb tide on 26 September.

26 September Ebb Tide

- 1.6 m wavelengths
- 5-10 m wavelengths
- 1 m/s

Along Channel distance (m)

Current Magnitude (m/s)
As before with the currents shown in figure 3-6, we can separate all the \( u_* \) values based on tidal cycle. Table 3-1 shows the mean \( u_* \) and range defined as one standard deviation, the total number of observed profiles, \( N \), that contributed to the estimates, and the mean Shields parameter obtained with (3.2) for spring-flood, spring-ebb, neap-flood, and neap-ebb tides. In all cases, estimated \( \theta \) exceeded the critical \( \theta_c \) indicating that the threshold for incipient motion is generally exceeded. Results indicate greater \( u_* \) and higher \( \theta \) during neap-flood than neap-ebb, which is consistent with observed onshore migration of sand dunes during neap tide (Chapter 2). Similarly, \( u_* \) and \( \theta \) values are larger for spring-ebb than spring-flood, consistent with the net seaward migration of the sand dunes during spring tides. Furthermore, the \( u_* \) and \( \theta \) estimates are strongest during the spring-ebb tides, which is also consistent with the observed net offshore migration of the sand dunes over the entire study period. The Rouse parameters suggest during neap tides sediment is transported by bedload, however during spring tide sediment is 50% suspended load and 50% bedload.

Table 3-1. Shear stress estimates, mean \( u_* \)-values and Shields parameters, averaged according to tidal stage. \( N \) represents the number of observations used in the mean. \( R_o \) is the average Rouse number calculated using the mean \( u_* \)-values.

<table>
<thead>
<tr>
<th></th>
<th>Neap</th>
<th></th>
<th>Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N )</td>
<td>( u_* ) (m/s ± 1( \sigma ))</td>
<td>( \theta ) (± 1( \sigma ))</td>
</tr>
<tr>
<td>Flood</td>
<td>16</td>
<td>0.09 ± 0.04</td>
<td>0.75 ± 0.59</td>
</tr>
<tr>
<td>Ebb</td>
<td>31</td>
<td>0.05 ± 0.02</td>
<td>0.26 ± 0.22</td>
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</tbody>
</table>
3.5 Discussion

Observations of currents in many inlet and shallow water environments in the world are limited due to the difficulty of using traditional survey equipment in extremely shallow and dynamic environments. Results show that mean currents obtained from the CBASS can be used to accurately quantify the vertically varying flow field in shallow, dynamic inlet environments with strong flows. The advancement in small maneuverable survey systems will allow more field data from inlets and shallow water coastal regions to be collected and used to verify and advance computer models of coastal hydrodynamics.

Aerial photographs of Hampton Harbor Inlet indicate that the large sand dunes extend outside of the navigation channel (discussed in Chapter 2), suggesting their evolution is a consequence of transport and dynamics that involves the entire inlet. The depths outside of the navigation channel are shallow, approximately 1 m, and thus it is not possible for traditional survey vessels with relatively large drafts and lower maneuverability to obtain data across the entire inlet. One limitation of this study was that MBES bathymetry was not collected outside of the navigation channel, and that currents and bathymetry were not always collected at the exact same times. Transitioning the MBES system to the CBASS (a process underway) will allow for coincident bathymetry and current measurements over the entire width of the inlet, allowing for a better observation of the coupled sediment transport system.

The examples shown in figures 3-3 and 3-4 highlight the advantage of using a moving platform to measure mean currents over relatively large areas. Flow fields with strong horizontal variation are not easily quantified with fixed instrumentation.
example, the bottom-mounted ADCP at line 8 (Figure 3-4) was not placed in a location to measure the strongest flow emanating from the inlet during ebb tides (located at about coordinate 300 m along line 8). On the other hand, the CBASS is able to measure the horizontal structure of the current variation. The trade-off, of course, is that the temporal resolution is not easily quantified with moving vessels, and clearly a combination of the two is the optimal way to examine current structure in regions similar to Hampton Harbor Inlet.

Wave conditions during the surveys were mild, with rms wave heights, $H_{rms}$, of 0.22 m and 0.17 m and mean wave periods, $T_m$, of 10.3 s and 9.2 s, at ADCP 1 and ADCP 2, respectively. These conditions correspond to surface rms wave orbital velocity amplitudes of about 10 cm/s. These velocities are on the order of 10-20% of the mean flows at the ADCP locations, but are filtered out through multiple passes along the transect (as in Szupiany, et al., 2007). During greater surface wave conditions, the orbital velocities become larger and their effects on current measurement can be problematic. The averaging technique used for this study, following work by Szupiany, et al. (2007), seems to work well with errors staying about the same for smaller wave conditions. Although wave orbital velocities were greater during large wave conditions (Figure 3-2), the large waves were limited to offshore locations through refraction and breaking. Therefore, surface waves are expected to have little impact on the current measurements made within the inlet.

The rough nature of the inlet seafloor, characterized by the presence of large sand dunes and smaller, ubiquitous mega-ripples, creates complex bed geometry. The complex bed morphology is generated by the strong tidal currents, but also feeds back
into the vertical and horizontal structure of the flow. Current patterns observed along the main inlet transect (Figure 3-9 and 3-10) reflect the seafloor profile, with vertical structure that varies in response to the bedform patterns. From a qualitative standpoint, the currents vary as a function of sand dune crests and troughs. The mean along-inlet currents on 28 September during a flood tide are weaker over the crests of sand waves than the troughs, which is somewhat surprising considering the constriction of the flow vertically over the crests induced by mass balance. This observation suggests that three-dimensional circulation is present throughout the inlet, but is not easily quantified with limited (albeit repeated) sampling along the same along-inlet transect. The presence of strong lateral shear in the main current down the center of the channel further suggests cross-inlet processes may be important to the flow patterns and related sediment transport. Certain instabilities will be supported by this shear, although it is not clear how that process will be manifested. There is evidence of three-dimensional evolution to the sand dune field discussed briefly in Chapter 2, but it is limited in scope to the narrow channel.

In addition to varying spatially over the length of the inlet, currents vary temporally with the fortnightly tidal cycle. The observed pattern of strong currents during neap-flood and spring-ebb tides is consistent with the observed migration directions of the sand dunes discussed in Chapter 2. However, sediment is clearly being transported on a larger scale throughout the inlet, and depends more on the shear stress at the bed than the relative magnitude of the currents. The Shields parameter was always observed to be much greater than the critical Shields value (estimated from the literature), so incipient motion is in general is always occurring. This is perhaps not unexpected for the
Hampton Harbor Inlet, which is well known for large current flows and sediment transport that results in the need to dredge the channel every few years (PDA, 2012). This study shows that observed friction velocities varied temporally as a function of tidal stage, with higher $u_*$ and Shields parameters during spring-ebb tides (compared to spring-flood) and neap-flood tides (compared to neap-ebb), suggesting more sediment is being transported seaward during spring tides and onshore during neap tides.

In future work, shear stress estimates will also be estimated from sand dune migration rates. A simple bed load transport model introduced by Meyer-Peter and Müller, 1948, will be used to approximate an independent estimate of shear stress, $\tau_{\text{MPM}}$, with,

$$\tau_{\text{MPM}} = \rho \left[ \frac{Q(s-1)g}{A_{\text{MPM}}} \right]^\frac{2}{3}$$

(3.5)

In the above equation water density, $\rho = 1000$ kg/m$^3$; specific density of quartz, $s = 2.65$ kg/m$^3$, gravity $g = 9.8$ m/s$^2$, $A_{\text{MPM}}$ is an assumed a constant with value of 10, and $Q$ is the sediment transport rate given by,

$$Q = Q_0 + n c_b z_{hc}$$

(3.6)

where $Q_0$ is the sediment transport at the bed, which is assumed to be zero, sediment concentration $n = 0.7$, $c_b$ is bedform celerity; and $z_{hc}$ is the elevation of the bedform from baseline to crest (Nielson, 1992). Estimates of bedform elevation will require setting a baseline elevation of each sand dune. Seafloor roughness elements will have to be accounted for when setting the baseline, and variation in mega-ripple size and
distribution will introduce uncertainties into sand dune elevation estimates. Additionally, bedform celerity estimates will have to assume that bedform migration occurred steadily in one direction between successive surveys. Bathymetry surveys were not continuous, so this assumption also introduces uncertainty in shear stresses estimated using the Meyer-Peter and Müller model.

Shear stresses estimated from the log boundary layer method are very high, indicating sheet flow at times. Estimates of shear stress from the Meyer-Peter and Müller model will help to confirm that the shear stress estimates provided in this study are accurate. Although shear stresses estimated from the log boundary layer method and the Meyer-Peter and Müller model will likely be different, slight differences in shear stress values can be attributed to geographic variation between where the currents were measured and where the bedforms were analyzed.

3.6 Conclusion

Observations of mean current profiles were obtained in the narrow, strong tidally modulated Hampton Harbor Inlet in southeastern New Hampshire in the Gulf of Maine over a 22 day period in the fall of 2011. Current profiles were collected during 10 survey days with a 1200 kHz RDI Workhorse ADCP mounted on a GPS-based personal watercraft, known as the Coastal Bathymetry Survey System or CBASS. Transects across and along the inlet were used to characterize the mean flow patterns as a function of tidal phase.

In order to average out transient currents associated with surface gravity waves and other relatively high frequency motions due to eddies, up to ten consecutive passes
(typically taking 15-60 min to complete) along each transect were averaged together in 50 percent overlapping spatial bins, 30 m by 30 m. The current profiles in each spatial bin spanned the water column with 0.5 m vertical resolution. To verify the accuracy of the current profiles, data were obtained with the CBASS directly over bottom-mounted ADCP's in two locations and compared. Currents obtained with the CBASS were found to have accuracies relative to the bottom-mounted ADCP's of within rms errors of 0.045 m/s in magnitude and 17 deg in direction, and can be used to accurately quantify the vertical structure of the flow field.

Along and cross-inlet transects capture the spatial character of the inlet currents at various stages of the tides. The spatially varying current structure of transects along the central navigation channel transect shows a strong relationship to the location of large sand dunes oriented perpendicular to the channel. Transects over the 22 day period were categorized as spring-flood, spring-ebb, neap-flood, or neap-ebb. Flood tidal currents accelerate into the narrow mouth of the inlet during both neap and spring tides, while ebb tides flow extend far offshore the inlet as a result of the inertia from the pressure driven currents exiting the inlet. Spring tidal currents are much stronger than neap flows as expected from the larger tidal ranges.

The vertical structure of the currents was used to estimate friction velocities by fitting the bottom boundary layer to a logarithmic profile. Estimates of frication velocities were used to estimate Shields entrainment parameters for the coarse grained, quartz sand in the inlet. Observed friction velocities and Shields parameters averaged over the tidal cycles indicate stronger sediment entrainment during spring-ebb (compared to spring-floor) and neap-floor (compared to neap-ebb). These observations are
consistent with observed sand dune migration rates and directions obtained during the same field experiment with high resolution multibeam echosounder surveys.
CHAPTER 4

CONCLUSIONS

Observations of bedform migration and mean tidal currents were obtained in the Hampton Harbor Inlet in the fall of 2011. Seafloor topography from within the inlet navigation channel was observed with a total of nine bathymetric surveys obtained over the four-week study period. Survey data was found to have a maximum noise floor of 0.05 m, and was capable of resolving seafloor bedforms greater than 0.5 m in wavelength. Observations show that the navigation channel is characterized by the presence of sand dunes that range in amplitude from 1-2 m and have wavelengths of 20-40 m, and smaller mega-ripples, with 0.1-0.3 m amplitudes and 1-10 m wavelengths. Mega-ripples are located in both flat portions of the inlet and superimposed on top of the sand dunes.

A series of 8 large coherent sand dunes migrated onshore and offshore with the fortnightly tidal cycle. The location and shape of the sand dune crests were analyzed with a variety of crest-mapping techniques. The shapes of sand dune crests vary spatially over the extent and width of the inlet, and also as a function of seafloor roughness elements. The sand dunes were observed migrating onshore during neap tides and offshore during spring tides. Net migration of sand dunes was up to 15 m offshore over the study period.
The resolution of the surveys was not fine enough to determine individual mega-ripple migrations, so seabed roughness element were characterized by integrating wavenumber spectra over wavelengths between 1-5 m and 5-10 m. Spatial variation in seafloor roughness indicated that mega-ripples grew in rms amplitude during spring tides and decayed in amplitude during neap tides. Mega-ripples also varied spatially throughout the inlet, with a higher concentration of mega-ripples located 300-500 m offshore of the Hampton Harbor bridge, and few-to-no mega-ripples located offshore of a stone jetty bounding the northern extent of the inlet.

The net movement of the sand dunes over the four-week study period was 10-15 m seaward, indicating that higher flowing ebb tides were dominating sediment transport in the inlet. To verify these observations, mean currents were collected simultaneously to the bathymetry surveys using an acoustic profiler mounted on a personal watercraft. Mean currents measured from the small moving platform were compared to mean currents measured from continuously recording bottom-mounted current profilers. There was good correlation between the bottom-mounted and moving mean current measurements, suggesting that mean currents were accurately measured from the personal watercraft. Mean current measurements taken from within the inlet, using the personal watercraft, indicate that maximum tidal currents exceeded 1.5 m/s and occurred during spring-ebb tide. Maximum currents observed during neap tides were 1.0 m/s and occurred during the flood tide.

Estimates of shear stress were determined with friction velocities and Shields parameters derived from a logarithmic fit to current profiles. The shear stress estimates were compared to observations of bedform migration, and were found to be consistent
with the patterns of onshore and offshore migration observed throughout the study. Furthermore, the effects of bedform variability on the vertical flow structure through the inlet were investigated. Analysis of the spatial distribution of the bedforms indicates mean current magnitudes in the along channel direction increase over sand dune troughs with lower seafloor roughness, and decrease over sand dune crests, suggesting a three-dimensional circulation pattern in the inlet.

The observations and conclusions drawn from this work can be used to further understand bedform migration in the Hampton Harbor Inlet. Observations can also be used to validate and improve upon inlet dynamic models, in particular sediment transport models. This work can be improved upon by expanding surveys to include bathymetry measurements outside of the inlet navigation channel, and also through collecting observations of both seafloor topography and mean currents during low tide. Additional field measurements can be used to improve understanding of bedform migration in dynamic tidally modulated inlets.
LIST OF REFERENCES
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APPENDICIES
APPENDIX A

UNCERTAINTY ANALYSIS

Static Total Propagated Uncertainty (TPU) estimates were calculated using a TPU uncertainty model built into Caris HIPS version 7.1. The TPU model calculates horizontal and vertical uncertainty values associated with each depth sounding, using an algorithm to estimate the total variance of the horizontal and vertical components of each individual uncertainty parameter associated with the survey. User defined survey specific parameters were input into the TPU model, these include attitude uncertainty, position uncertainty, and sound speed uncertainty. The Caris TPU model uses a built in acoustic model of the Imagenex Delta-T to estimate range uncertainties, as a function of beam angle, associated with the MBES. The Imagenex Delta-T acoustic uncertainty model built into Caris has not been verified, therefore the modeled uncertainty estimates provided by the Caris TPU model are not an accurate representation of uncertainty. An acoustic uncertainty model for the Imagenex Delta-T was developed using data from this study, and will be discussed later. First, the methods used to estimate the user defined uncertainties input into the TPU model, including sound speed, position, and attitude uncertainty, are described.

Sound speed uncertainty was estimated using a numerical simulation method developed by Beaudoin et al., (2009). The numerical simulation method was applied to the sound speed profiles using the software application, SVP Editor, developed and
maintained by the Multibeam Advisory Committee, established under the United Nations Convention on the Law of the Sea. The numerical simulator mimics the ray trace of the MBES and determines the effect of water column variability on the soundings. The sound speed profiles and the ray traces for casts made during the surveys are shown in Appendix B. The deepest common depth of each cast was used to determine sound speed uncertainty by taking the standard deviation of the horizontal and vertical components of each ray trace. Sound speed uncertainty was determined by taking the largest standard deviation calculated for a day over the entire survey period (Table A-1).

Attitude and GPS positioning rms uncertainty were calculated during post-processing using the POSpac software. The mode rms uncertainty value of each survey was determined and then the mean of the mode values was used to estimate a total survey period rms uncertainty value. (Table A-1).

Table A-1. Average study uncertainty values in position and attitude. The TPU estimates are computed using an acoustic uncertainty model that has not been verified; therefore this TPU estimate represents the very upper bound of uncertainty, and will be much lower if a correct acoustic uncertainty model is applied.

<table>
<thead>
<tr>
<th>RMS Roll Uncertainty</th>
<th>0.007°</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS Pitch Uncertainty</td>
<td>0.007°</td>
</tr>
<tr>
<td>RMS Heading Uncertainty</td>
<td>0.026°</td>
</tr>
<tr>
<td>North Position Uncertainty</td>
<td>0.012 m</td>
</tr>
<tr>
<td>East Position Uncertainty</td>
<td>0.011 m</td>
</tr>
<tr>
<td>Down Position Uncertainty</td>
<td>0.024 m</td>
</tr>
<tr>
<td>Horizontal Sound Speed Uncertainty</td>
<td>0.012 m</td>
</tr>
<tr>
<td>Vertical Sound Speed Uncertainty</td>
<td>0.007 m</td>
</tr>
<tr>
<td>Total Propagated Uncertainty*</td>
<td>1 m</td>
</tr>
</tbody>
</table>
An acoustic uncertainty model of the Imagenex Delta-T MBES was estimated using a paired estimation method (Dieck, 1992). Ranges to the seafloor along each beam, at 2 deg angle increments, are determined using depth-finding algorithms with the Imagenex Delta-T software. Estimates of range variance as a function of beam angle is determined from the difference between two successive pings using,

\[ \sigma(\theta) = \frac{1}{2} \sigma_{12}^2(\theta) \]  

(A.1)

where \( \sigma_{12}^2(\theta) \) is the variance of 300 consecutive pings of a beam increment (\( \theta \)). Figure A-1 shows a plot of the standard deviation of the range values as a function of beam angle, also known as the acoustic uncertainty model, for a sample of a survey collected on 17 October, 2011. The outer beams of the Delta-T (near \( \pm 60 \) deg), did not always produce a good return owning to weak acoustic backscatter intensity and elevated noise at the outer beams. Therefore, acoustic range uncertainty was not conducted beyond 55 deg from nadir. Once this acoustic uncertainty model can be applied to the TPU model, a more accurate estimation of relative total propagated uncertainty can be made.
Figure A-1. Acoustic uncertainty model for 17 October at 1359 local time. Acoustic uncertainty around nadir is approximately 2 to 2.5 cm, however at 50 deg and -50 deg the uncertainty increases to approximately 5 cm.
APPENDIX B

SOUND SPEED CASTS AND RAY TRACING PLOTS

The sound speed casts and ray tracing paths from the SVP editor for each survey data are shown in the following figures. The left panel shows the ray traces, and the right panel shows the sound speed casts, both as a function of depth. The common depth each cast was analyzed to is shown with a red dot on the ray trace plots.
26 September

Elevation of cast below water surface (m)

Distance (m)

Sound Speed (m/s)

-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6

100
28 September

Elevation of cast below water surface (m)

Distance (m) Sound Speed (m/s)

+1.509e3
Elevation of cast below water surface (m)

Distance (m)

Sound Speed (m/s)

03 October

-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
-5.5

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
+1.5047e3
APPENDIX C

AVERAGE NOISE FLOOR CONTROUR PLOTS

21 September

26 September

28 September

30 September

03 October

05 October

17 October

Along-channel distance (m)

Across-channel distance (m)

200 400 600 800

Along-channel distance (m)

0 m

0.02

0.04